Oxygen budget for the North-Western Mediterranean deep convection region

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Responses to the comments of Toste Tanhua, the Reviewer 2

First we would like to warmly thank Toste Tanhua for his relevant comments and precious recommendations which will improve the manuscript.

Answers to the reviewer' comments are reported point by point. The questions and comments of Toste Tanhua are in *blue*, the answers in black and the modifications proposed in the revised manuscript in *black*.

The paper use a model to estimate the oxygen budget for the NW Mediterranean ,and use a range of relevant field data to validate the model. The paper is very well organized and written, the logical structure is very helpful to navigate this comprehensive study. I am impressed by the overall very high quality of the paper, that covers a very relevant and significant topic. There are only a few things that could be considered in a minor revision.

Reply: We appreciate the positive assessment of the reviewer.

The main issue is that the paper do not take the bubble effect into account. In a recent paper by Atamanchuk et al. (2020) this is discussed, and the authors conclude that " By neglecting the bubble-mediated flux component, global models may underestimate oxygen and atmospheric potential oxygen uptake in regions of convective deep-water formation by up to an order of magnitude." I realize that this paper was published very recently, but a short discussion on the significance of bubble-mediated flux, and what it might mean for this study, would be appropriate.

Reply: In the first version of the manuscript we presented the results of a sensitivity study on the parameterization of the oxygen flux at the air-sea interface. Two of these parameterizations, the ones proposed by Liang et al (2013) and by Bushinsky and Emerson (2018), include components of bubble-mediated fluxes. Using the parameterization proposed by Liang et al (2013) we obtained flux estimates that are in the upper range of all estimates, whereas using that of Bushinsky and Emerson (2018) the flux estimates are in the lower range. To answer more precisely this question we have performed two new sensitivity tests with the "bubble inclusive" parameterizations of Woolf (1997) (hereinafter W97) and Stanley et al (2009) (hereinafter S09), that gave ones of the best estimates in the study on the Labrador Sea by Atamanchuk et al. (2020). Both of these new tests provide estimates of annual air-sea flux in the upper range of all estimates (20.1 mol m^{-2} yr^{-1} with W97 and 21.5 mol m^{-2} yr^{-1} with S09). In agreement with the study by Atamanchuk et al. (2020), our results with the parameterization of Stanley et al. (2009) shows, when compared to the fluxes obtained with the parameterization of Wanninkhof et al. (1992), an atmospheric oxygen uptake that started earlier in autumn, stronger fluxes in winter during peak wind periods and less outgassing in summer (Figure 1). The ratio between the two flux estimates can reach ~7 in late October, but in winter it is generally less than 2. The ratio between the two annual averages of air-sea flux, of 1.2, is less strong in our results for the northwestern Mediterranean Sea than in those obtained by Atamanchuk et al. (2020) for the Labrador Sea. This can be explained by a diffusive flux that remains significant due to the very strong undersaturation which varies between -10% and -20% on average during deep convection period over the whole studied zone (Fig. 7c of the submitted manuscript). In the Labrador Sea the undersaturation reported by Atamanchuk et al. (2020), ranging from -5% to -8%, is lower. The difference in wind intensity could also explain this difference in the ratio since this ratio reaches its largest values during days with strong wind speeds. Atamanchuk et al (2020) reported that at least 40 days during the year under study were marked by wind speeds of more than 13.8 m/s. In our study, no grid point in the zone has 40 days with wind speeds greater than 13.8 m/s. We have calculated that during the year 2012-2013 the number of days with wind speeds greater than 13.8 m/s varies between 30 and 35 days over an area representing 13% of the convection zone, located north of the central zone.

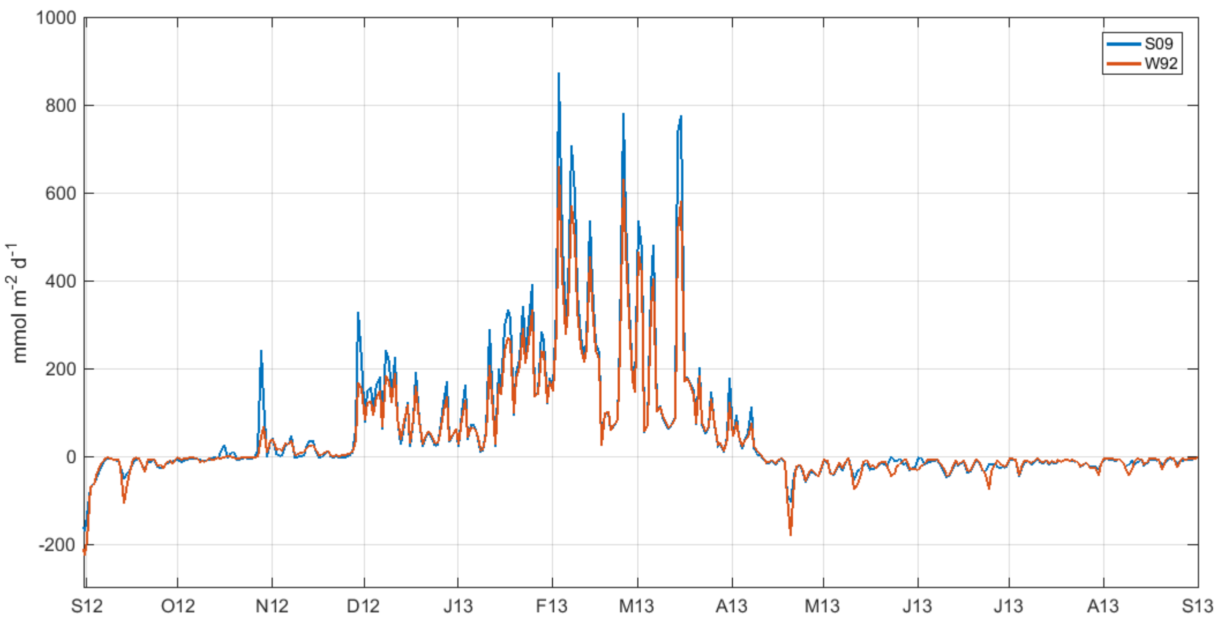

Figure 1: Time series over the period September 2012-September 2013 of air-to-sea oxygen fluxes (mmol m^{-2} day^{-1},) estimated using the parametrizations of Stanley et al. (2009) (blue) and of Wanninkhof et al. (1992) (red), spatially averaged over the northwestern Mediterranean convection area (red).

Finally, the estimates of annual air-sea flux (20.0 mol m^{-2} yr^{-1}) obtained in the standard run with the “diffusive only” parameterization of Wanninkhof and McGillis (1999) are quite close to those obtained with the Stanley et al (2009) and Woolf (1997) parameterizations. This can be explained also by the strong undersaturation during the convection period and by the cubic dependence of wind speed of the Wanninkhof and McGillis (1999) parameterization. An experimental study of flux measurements in this region over an entire year would allow a better assessment of the different parameterizations.

In the revised manuscript, we will add the results of the two new sensitivity tests and references to the study of Atamanchuk et al. (2020). Modifications will therefore be made in Sections 2.1.2 (description of the biogeochemical model) and 6.1 (discussion on air-sea oxygen flux). In particular, as suggested by the Reviewer, we propose to add the following small discussion in Section 6.1:

“Previous studies on oxygen air-sea flux in deep convection zones recommend the use of parameterizations with high transfer during periods of strong wind and convection (Copin-Montégut and Bégovic, 2002; Körtzinger et al., 2008b; Koeling et al., 2017; Atamanchuk et al., 2020). Atamanchuk et al. (2020), comparing air-sea flux estimates based on various parameterizations, found that these flux estimates may vary by an order of magnitude and warn of the possibility of a strong underestimation of oxygen air-sea flux in biogeochemical models that do not include bubble-mediated flux. In our study, the range of estimates obtained with both types of parameterizations, those that are only diffusive and those that include a bubble-mediated term, is similar. Although the parameterization of Wanninkhof and McGillis (1999) used in our standard run does not include an explicit bubble-mediated transfer term, it provides with estimates of air-sea fluxes close to those obtained with the bubble-inclusive one of Stanley et al (2009), preferred by Atamanchuk et al. (2020) in their Labrador Sea study. The strong undersaturation obtained in the north-western Mediterranean during the convection period, between -10 and -20%, may explain a greater contribution of the diffusive flux compared to the air injection by bubbles. Moreover, winter conditions are less extreme than in the Labrador Sea where strong wind speeds greater than 13.8 m/s were encountered for at least 40 days. In the north-western Mediterranean Sea, only 13% of the convection zone was characterised by a number of days with wind speeds > 13.8 m/s varying between 30 and 35 days, in winter 2013. An experimental study of flux measurements in this region over an entire year would allow a better assessment of the contribution of air injection in the total air-sea flux and hence of the use of different gas transfer parameterizations.“

Minor comments:

Line 34: I am not sure that reduction of deep convection related to climate change has been proven, although increased stratification etc. has .

Reply: Changes in circulation and convection were identified as major factors responsible for the ongoing observed and modelled deoxygenation (Plattner et al., 2002; Joos et al., 2003). The study of Brodeau and Koenigk (2016), based on an ensemble of 12 climate model simulations shows that deep convection in the Labrador Sea started to weaken in the beginning of the twentieth in response to warming atmospheric conditions. Using observations and an ensemble of 36 simulations of CMIP5, de Lavergne et al. (2014) suggested that the activity of deep convection in the Weddell Sea was reduced under anthropogenic changes. However other reasons than climate change were also proposed by the authors to explain this decline. Therefore to take into account this comment we will modify this sentence.

Line 56: "Massive supply of nutrients" – I guess this is by Mediterranean standards, having low nutrient concentrations in comparison to North Atlantic for instance. I agree with the statement, but maybe it needs to be put in context.

Reply: We agree that the importance of nutrient input associated with the deep convection process should be put in the context of the oligotrophy of the Mediterranean Sea. Therefore we will modify the sentence in the revision as follows:

"At the Mediterranean basin scale, the NW deep convection is one of the major processes responsible for an enrichment of nutrients of the euphotic layer, comparing to Atlantic influx as well as terrestrial and atmospheric inputs (Severin et al., 2014; Ulses et al., 2016; Kessouri et al., 2017). "

Line 521: There is a recently published update of the Schneider et al 2014 paper that you could consider citing, and use as it contains data after 2012 (Li and Tanhua, 2020).

Reply: We thank the Reviewer for this information. The results shown in the article of Li and Tanhua (2020) complete the description of the ventilation of the western Mediterranean after 2011. We will cite these results in the discussion of our results in the revised manuscript as proposed here:

"New oxygenated waters were also observed in the entire deep layers of the Algerian sub-basin in 2011 (Schneider et al., 2014; Stöven and Tanhua, 2015), 2014 (Keraghel et al., 2020), 2016 and 2018 (Li and Tanhua, 2020). Moreover, the results of Li and Tanhua (2020) showed a ventilation of the deep waters of the Tyrrhenian Sea through an overflow of well-oxygenated water masses from the Algerian basin into the deep layer, between 2011 and 2016."

Finally, we would also like to point out that we have found an error regarding the trajectory and the name of the float for which the temporal evolution of the oxygen content is shown in Figure 5b. We apologize for this error that will be corrected in the revised manuscript.

References:

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